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The solid-state heat-capacity laser

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Abstract: Heat-capacity operation of a laser is a novel method by which high average powers can be generated. In this paper, we present the principles behind heat-capacity operation, in addition to describing the results of recent experiments.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.5680) Rare-earth and transition-metal solid-state lasers

1. Introduction

In order to understand the concepts behind heat-capacity operation of a laser, let s consider three modes of laser operation. The first is what is known *as single-shot* operation in which the time between firings is very long. High-power/high-energy lasers such as the National Ignition Facility laser at Lawrence Livermore National Lab are operated in this mode. Here, thermal effects in the solid-state lasing medium are not considered and ambient cooling of the laser medium occurs after the shot. The prime power source supplies lasing power only and the beam propagates in the absence of thermal cooling gradients.

The second mode of operation is known as *steady-state* operation. This is the typical operating mode for gas ion lasers and certain solid-state lasers such as Nd:YAG or Nd:YLF. To enable operation, the lasing medium is cooled at the same time it is being pumped. As a result, the prime power must supply both lasing *and* cooling power and the beam propagates in the presence of thermal cooling gradients.

The *heat-capacity* mode of operation[1] is intermediate between these two regimes. Here, laser operation rapidly adds single shots and the waste heat is stored in the lasing medium. The prime power supplies first lasing, and then cooling needs. Because the laser is operated in the absence of thermal cooling gradients, there are far less stresses induced on the lasing medium and optical distortions are minimized. If, in addition, the laser medium is face-pumped then compressive stresses occur at the surface. This minimizes the possibility of fracture in the medium.

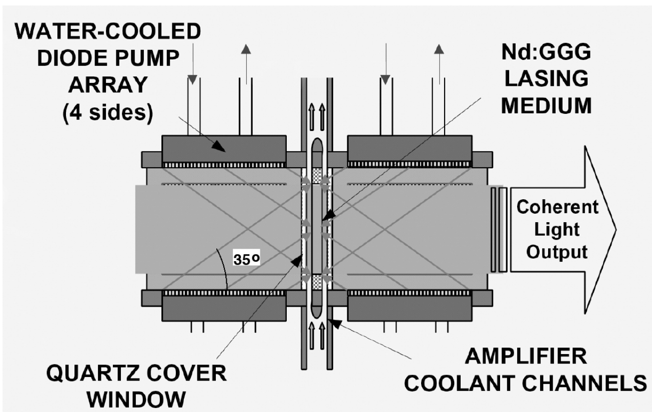
2. The three-slab diode-pumped HCL

As an initial scientific proof-of-principle, we constructed a flashlamp-pumped, Brewster-angle, Nd:Glass heat-capacity laser (HCL). This laser produced 500 J/pulse at a repetition rate of 20 Hz for a duration of ten seconds. We used an unstable resonator with a magnification of 1.5; the output beam thus consisted of a square annulus nominally 10cm on a side. The path chosen to achieve good beam quality during the ten-second run is to use an intra-cavity deformable mirror. An intra-cavity beam splitter sends part of the beam to a Shack-Hartmann wavefront sensor. Information from the sensor is analyzed to determine the actuator settings on the deformable mirror.

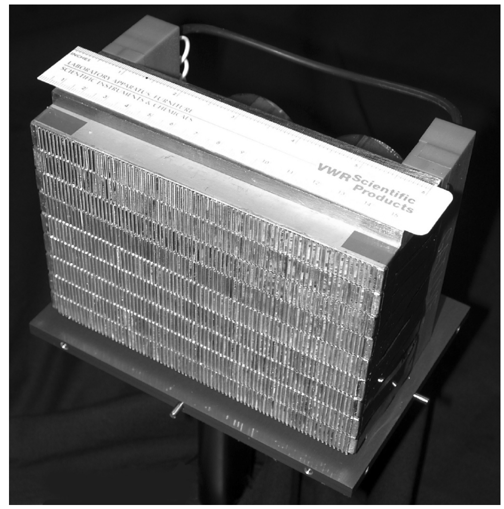
A major milestone in the SSHCL program is the construction of a very high power SSHCL that can be rapidly cooled between bursts. In order to achieve the desired output power, several changes need to be made in the design of the laser. The requirement of rapid cool down forces one to abandon glass as a lasing medium (since thermal diffusivity of glass is relatively low) and replace it with crystalline media. In an HCL, the path to higher power is not through the conventional method of increasing the energy/pulse, but rather by increasing the pulse repetition rate. Thus the new laser will still operate at 500 J/pulse, but now the pulse repetition rate will be increased from the present 20 Hz. This regime requires us to abandon flashlamps as a pump source and replace them with laser diodes..

Both these changes actually result in a laser system that is far more efficient than the flashlamp-pumped system described above. We have identified Nd:GGG (Gallium Gadolinium Garnet) as the laser material of choice due to its high thermal diffusivity (roughly 10x greater than glass)[2], greater emission cross-section (5x larger than glass), and greater fracture stress (5x larger than glass)[3]. In addition GGG has the advantage that large slabs may be cut from the boule. Another potential laser medium, YAG, has regions of high stress/depolarization in the boule that severely limit the size of the slab that may be extracted. A conceptual diagram of a building block for the diode-pumped Nd:GGG laser is shown in Fig. 1. We note that in contrast to the Nd:Glass 10 kW laser, here the laser slabs are normal to the beam propagation direction. This results in not only a more compact system, but one in which wavefront distortions due to thermally-induced slab deformations are drastically reduced.

In Fig. 1(b), we show a full-size laser diode array, as obtained from Armstrong Laser Technology. The array shown consists of 9 rows of 80 laser diode bars/row operating at a wavelength of 808 nm. Each bar is capable of delivering slightly over 100 watts of peak optical power; the array as a whole can produce approximately 75 kW of peak optical power. We have operated the arrays for several minutes at a time at a 10% duty factor, thus obtaining 7.5 kW of average optical power.



(a)

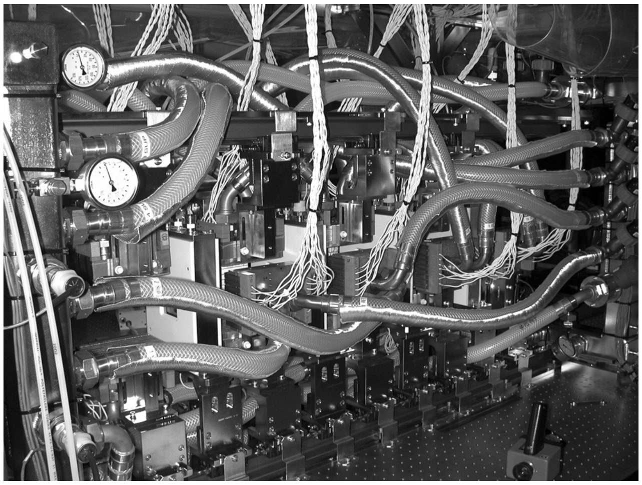


(b)

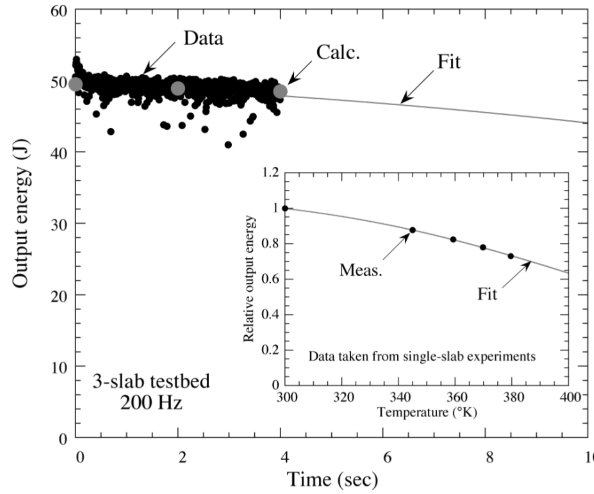
Fig. 1. (a) Pump geometry of diode-pumped Nd:GGG HCL. Each slab is pumped by four diode arrays. (b) Typical laser diode array. The array shown produces approximately 75 kW of peak optical power. A six-inch rule lies on top of the array.

A photo of the three-slab testbed is shown in Fig. 2(a). The large tubes shown in the photo carry cooling water for the laser diode arrays. The Nd:GGG slabs are housed in the vertical assemblies, the faces of which are fabricated from Macor, a ceramic that is robust enough to handle the intense optical radiation from the laser diode arrays. In its current configuration, we are using a stable resonator with a flat output coupler (15% transmission) and a 30m radius-of-curvature high-reflector. In order to maintain traceability to a field-ready design, the laser is operated from a 50 MJ (stored energy) Li-ion battery pack. At present, the (square) clear aperture is approximately 6.7 cm on a side. We are in the process of installing larger Nd:GGG slabs in order to obtain a 9.6 cm clear aperture. Since the output power from the laser simply scales with the aperture area, this change will allow us to obtain approximately twice as much energy as we get now.

In Fig. 2(b), we show a plot of the output energy from the testbed as a function of time during the course of a four second burst. The reduction in energy is due primarily to thermal population of the lower laser level. We see that at the beginning of the burst, we achieve an average output power of 10 kW (50 J/pulse @ 200 Hz repetition rate). Also shown on the graph are the results of calculations using our laser oscillator model as well as a fit which extrapolates the output energy to a ten second burst. The form of this fit is obtained from separate experiments where the output energy was measured as a function of slab temperature. The results of these experiments are shown in the inset graph along with the fit obtained. We have also operated the system with the Macor shields removed, in order to obtain an 8cm clear aperture. Under these conditions, we have achieved an average output power of over 16.5 kW. These tests also confirmed our assumption that the output power would scale with the aperture area.



(a)



(b)

Fig. 2 (a)Close-up of the diode-pumped three-slab testbed. The total length of the laser head, including cavity mirrors is approximately five feet. (b) Plot of output energy as a function of time for the three-slab testbed. Based on our measurements, the output energy should decrease slightly more than 10% over a ten-second burst.

3. Future plans and conclusions

As mentioned above, one of the major milestones in the HCL program is the construction of a high-power laser system. We used our energetics model to explore the trade-off between aperture size and number of slabs. The result of those calculations is shown in Table 1.

Table 1. Design space for a very-high-power laser system

Length of clear aperture (square) (cm)	Required output fluence (J/cm^2)	Number of slabs
11	4.5	14
12	3.8	12
13	3.2	10
14	2.8	9

In our calculations, we assumed an unstable resonator magnification of 2.0, a peak diode power of 100 W/bar, and 550 J output at the beginning of the burst. Our baseline design will use a 13cm aperture and a total of ten slabs. The laser system as a whole will want to tend towards smaller, more numerous slabs. This allows a higher gain/pass to be realized, which then allows one to operate at higher unstable resonator magnifications; a distinct advantage as far as alignment is concerned.

4. Conclusions

The operation of a solid-state laser in the heat-capacity mode is a novel approach to the development of systems which provide high-power, are compact, and most importantly, scalable. We have designed and constructed what we believe is the highest average-power diode-pumped solid-state laser to date. This laser produced an initial output power of 10 kW for a four second burst and 16.6 kW for a short half-second burst.

5. References

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[2] Chandrakant Baxi, General Atomics Corp. Private Communication
[3] H.C. Lee, Onyx Optics, Private Communication

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